Journal of Coastal Research | 15 | 2 | 399–412 | Royal Palm Beach, Florida | Spring 1999

Sea-level Lowstand in the Eastern Mediterranean: Late Pleistocene Coastal Terraces Offshore Northern Israel

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ABSTRACT

BELKNAP, D.F. and MART, Y., 1999. Sea-level Lowstand in the Eastern Mediterranean: Late Pleistocene Coastal Terraces Offshore Northern Israel. *Journal of Coastal Research*, 15(2), 399–412. Royal Palm Beach (Florida), ISSN 0749-0208.

A series of side-scan sonar surveys, seismic profiles and Remotely Operated Vehicle (ROV) observations along rocky terraces on the distal continental shelf off northern Israel encountered eolianite ridges with steep seaward escarpments and gentle landward slopes. The outcrops occur adjacent to the intersection of two major faults, trending NW-SE and NNE-SSW, and the terraces are a combination of terrigenous eolianites with carbonate biogenic overgrowths. Their lithology indicates that their depositional environment was coastal dunes, and their morphology was probably shaped by shore abrasion. This suggests that they formed in the coastal zone, when sea level was at least 100 m lower than the present. The depth of the terraces suggests correlation with the low sea-level stand of the latest Pleistocene (isotope stage 2). Since the eolianites at the distal shelf edge of Israel are commonly buried under recent sediments, the outcropping of the submerged lowstand shoreline at the intersection of two regional faults indicates tectonic activity along the faults off northern Israel during the Holocene. These terraces correlate with similar features produced worldwide at the late Pleistocene lowstand.

ADDITIONAL INDEX WORDS: *Eolianites, carbonates, neotectonic, side-scan sonar, ROV.*

INTRODUCTION

The coastal plain and continental shelf of Israel form a zone of low topographic relief that was submerged and exposed repeatedly during high and low sea-level stands during the Quaternary. Topographically, this zone extends from approximately 130 m below present sea level to nearly 80 m above it and MICHELSON (1970) even reported an early Pleistocene marine terrace at an elevation of 120 m on Mount Carmel, some 30 km south of Haifa. The coastal plain and continental shelf show similar patterns of geographic characteristics. They both attain their maximal width in southern Israel and wedge out northward (Figure 1). The region of Mount Carmel, in Haifa, is anomalous within this general geomorphological pattern. Here the present coastal plain is less than 100 m wide, and the continental shelf width is only 10 km (Figure 2). Both the coastal plain and the continental shelf become wider north of the Mt. Carmel promotory. The general pattern of northward narrowing resumes north of Akko (Acre).

Ridges of eolianite occur repeatedly along the coastal zone of Israel, on the coastal plain as well as on the shelf. The eolianites comprise Nilotic quartz sand with carbonate cement, with interlayered calcarenites and loam in places (YAALON, 1967; GAVISH and FRIEDMAN, 1969). Where these ridges crop out along the shore, they are cut by wave abrasion and a characteristic seaward-facing escarpment commonly develops. The dimensions of the escarpment vary from 2–10 m in northern Israel to 40 m in central Israel (EMERY and NEEV, 1960; NEEV *et al.*, 1976). The eolianite ridges are well exposed on land, but on the continental shelf they are commonly covered by an apron of unconsolidated sediments. Although their general features are evident in seismic profiles (ALMAGOR and ALMAGOR, 1984), outcrops are not abundant. One of the bathymetric features that is unique to the Haifa-Carmel continental shelf is a series of large promontories at the shelf break with several marine terraces at depths of 85–130 m that crop out through the sediment apron (ALMAGOR and HALL, 1984; EYTAM, 1988; MART and BELKNAP, 1991).

The sedimentological regime along the coastal plain of Israel is determined primarily by quartz and clay minerals from the Nile River drainage (POMERANCBLUM, 1966; STANLEY *et al.*, 1997). Longshore currents transport the quartz sand northward, forming littoral systems of parallel and crescentic bars. Onshore transport of the sand bars results in landward accretion, and eventual formation of sand dunes (GOLDSMITH *et al.*, 1982). The sand supply diminishes gradually northward, as the distance from the Nile delta increases. This sedimentological regime has prevailed since at least the early Pleistocene (EMERY and NEEV, 1960; NEEV *et al.*, 1976).

The recurring Pleistocene marine transgressions and regressions left behind a series of elongated eolianite hills, lo-

98004 received and accepted in revision 12 January 1998.

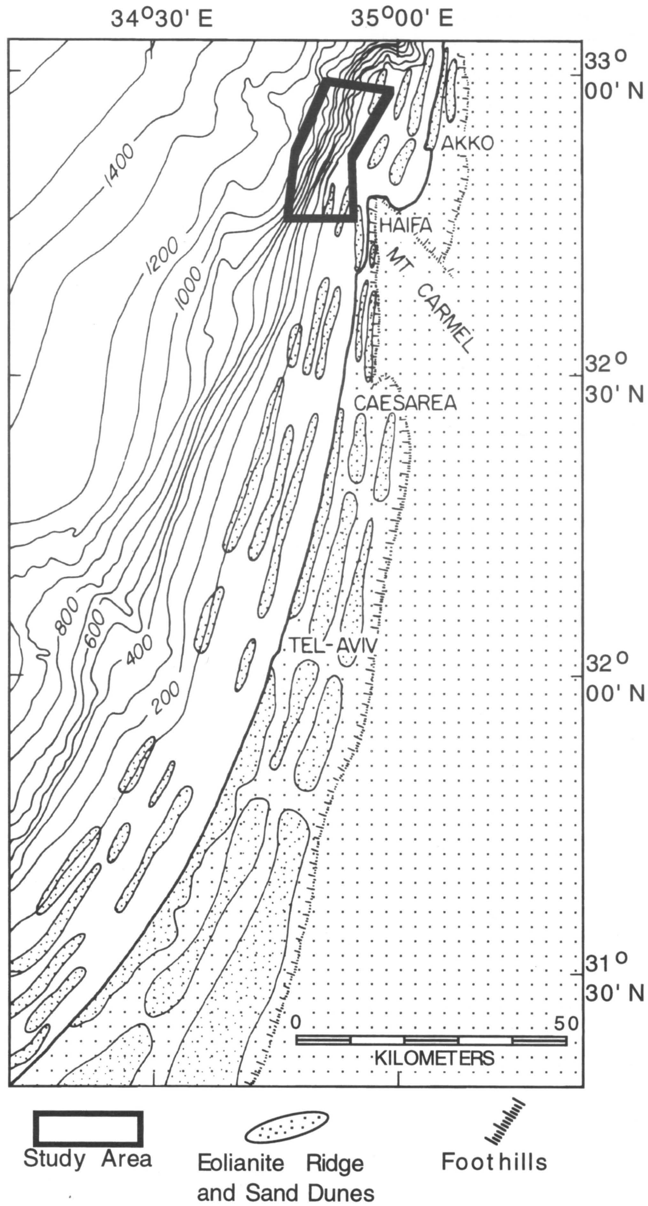

Figure 1. The coastal plain and continental shelf of Israel, showing the general trend of northward wedge-out. Mount Carmel promontory and Haifa Bay are anomalous to the general geomorphological pattern. Eolianite hills and active sand dunes are marked. Note the parallel trend of the eolianite ridges and the present shoreline.

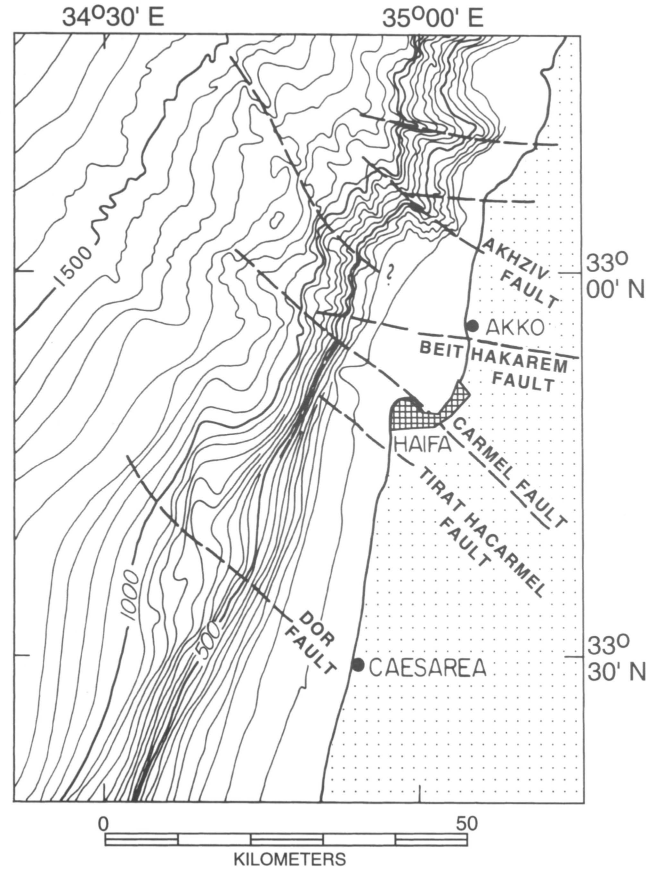

Figure 2. Bathymetric map of the Carmel Promontory and Haifa Bay, after Hall (1980). Heavy lines indicate major faults (Mart, 1984). Note the orthogonal pattern of faulting off Haifa.

cally known as "kurkar ridges," on the coastal plain and the continental shelf. The eolianite hills are fossil sand dunes (GAVISH and FRIEDMAN, 1969). Their stratification is characterized by extensive long, sweeping cross-bedding (AVNIMELECH, 1952), and they are interbedded with layers of red loam and with occurrences of calcarenite (NEEV *et al.*, 1987). The eolianites are abundant in the coastal plain of Israel, and the ridges are imprinted on it, forming series of coast-parallel lineations on land and at sea (NEEV *et al.*, 1976). The distribution of modern sand dunes shows a somewhat similar pattern: a prominent coastal dune extends parallel to shore, and irregularly oriented barchans occur farther inland. It seems that the eolianite ridges occur in a pattern similar to that of the active dunes, where the higher coastal dunes built a series of elongated hills trending nearly parallel to the coastline. Offshore submerged ridges show trends similar to the eolianite ridges cropping out on land (ALMAGOR and HALL, 1984), and on a ridge at the distal continental shelf off Haifa we observed cross-bedding typical of eolianites from ROV images (MART and BELKNAP, 1991).

The purpose of this study was to verify the occurrence of a submerged coastal terrace on the outer shelf, and to correlate it to onshore Pleistocene eolianite ridges. The identification of eolianites at the shelf break near 120 m depth extends the zone in which these coastal deposits have been identified in the region. This identification of coastal terrace deposit substantiates previous interpretations from seismic data (e.g., NEEVE *et al.*, 1976; ALMAGOR and HALL, 1984), and invites comparison to late Pleistocene coastal terraces elsewhere.

METHODS

Two phases of observations were performed on a submerged hill on the on the distal continental shelf off Haifa, known as "Navy Terrace" (EYTAM, 1988). In 1989, a set of reconnaissance dives with a Benthos Mark II ROV provided the first *in situ* video images and still photographs of bottom characteristics at the 100–130 m terrace edge. Navigation was by microwave ranging, providing 25 m precision. These results (MART *et al.*, 1990; MART and BELKNAP, 1991) indicated the presence of layered sedimentary rocks with abundant carbonate encrustations and modern sponge bioherms. Cross-bedded sandstone and possible coquina were observed.

In 1991, side-scan sonar maps were produced to delineate the characteristics of bottom sediments and rocky outcrops. We deployed an EG&G SMS 260 from the *R/V Shikmona*, using a 200 m armored cable that allowed nearly complete mapping in water depths less than 200 m. Navigation was by GPS, resulting in nominal 100 m or better precision. Two-hundred-and-fifty km of trackline with scales of 200–400 m to either side of the trackline were recovered (Figure 3). The EG&G SMS 260 provides a digitally corrected image, with slant-range and along-track distortions removed. Speed-over-ground was provided by analogue speed-log or by manual input from the GPS navigation when available. Images were manually transferred to an interpretive map (Figure 4) using preliminary dives to constrain bottom types. Later ROV dives were used to modify the preliminary interpretations. An ORE 132 3.5 kHz seismic reflection profiler was deployed at the same time as the side-scan sonar on the 1991 cruise. This provided bathymetric depths and subbottom returns of sufficient detail to determine sediment thicknesses. A bathymetric chart (Figure 5), more detailed than those previously available, was constructed from these uncorrected data to correspond with the location of the side-scan map.

In October, 1991, 12 ROV dives were completed at 8 sites within the side-scan sonar map area (Figure 3). The ROV was deployed with a tether to a down-weight station containing 50 m of free tether, in water depths from 120 to 60 m. Continuous video was photographed by either standard or close-up cameras in color, and annotated by verbal observations. Shipboard readouts provided depth, orientation, and camera tilt angle. Still photos were taken of items of interest. The ROV has limited sampling capability, but we were able to recover six loose rocks. Three of the sampled pebbles proved to be pieces of encrusting coralline algae (R. STENECK, *pers. comm.*, 1993) in small plates of a few mm thickness, cemented together.

GEOLOGIC SETTING

Geomorphology and Structural Geology

Haifa Bay is a wide and open embayment, protected by two promontories, the Carmel promontory to the south and the Akko promontory to the north (Figure 1). Its southern boundary is the mountain range of the Carmel, a major geomorphological and tectonic feature that rises steeply to 250–550 m above the coastal plain. The plain was down-faulted considerably and was subsequently filled by thick sedimentary series of marine, estuarine, marsh and talus deposits (SLATKINE and ROHRLICH, 1963; HOROWITZ, 1979). The northwestern edge of Mount Carmel reaches the sea (Figure 1), and bisects the coastal plain of northern Israel. The geomorphological and structural northern boundary of Haifa Bay is less conspicuous, however, Akko promontory controls the sedimentological regimes of northern Israel (Figure 2), forming a trap that checks the northward flow of Nilotic sand (GOLDSMITH and GOLIK, 1980). Haifa Bay is shallow, less than 25 m in most places. The shallow bathymetry of Haifa Bay belies its association with neotectonics that downdropped the coastal plain and uplifted Mount Carmel, but the thick Plio-Quaternary sediment fill is evidence for its intensive subsidence (MICHELSON, 1970). In some locations bathymetry is disrupted by a series of N-S trending eolianite ridges that protrude several meters above the silty seafloor (HALL and BAKLER, 1975).

Haifa Bay is the submerged part of a wedge-shaped structural rift, bounded by the NW-SE trending Carmel Fault on the south, and by the probable western extension of the E-W trending Beit-HaKarem Fault on the north (Figure 2). The vertical throw of the Carmel Fault is more than 1000 m, and since it clearly displaces Pliocene and Pleistocene strata (SLATKINE and ROHRLICH, 1963; 1966; KAFRI, 1970; ROHRLICH and GOLDSMITH, 1984), it is a young feature. Furthermore, an earthquake of magnitude M_b = 5.1 occurred along the Carmel Fault on August 24, 1984, indicating that the fault is still active. The Beit-HaKarem Fault, the northern structural boundary of Haifa Bay, strongly affects the morphology of the mountainous terrain of the Galilee region, displacing Cretaceous and Eocene strata, but its geomorphological effects along the coastal plain and Pliocene-Quaternary sedimentary rocks are not clear. Other faults that transect Haifa Bay and its coastal plain offset the older strata and also affect the configuration of the continental slope (ALMAGOR and HALL, 1984). However, they are not discernible in the late Quaternary sequences of the Bay and its coastal plain.

Another fault system that affects the continental shelf off Haifa is a series of NNE-SSW normal faults that controls the shelf break. The shelf-break faults were reported in many places off Israel, but they are conspicuously absent in some locations (NEEV *et al.*, 1976; GARFUNKEL *et al.*, 1979). These faults affect the shelf-slope transition off northern Israel, but their geomorphological effect diminishes gradually southward (BEN-AVRAHAM, 1978; MART, 1982; 1984).

Sedimentology

Haifa Bay is the northern terminus of the littoral sedimentary system derived from the Nile River (GOLDSMITH and GOLIK, 1980), characterized by the abundance of quartz sand and silt along the present coastal zone. Nilotic smectite clays are deposited in lower-energy marine environments (NIR, 1984). The quartz grains are transported along the Sinai and Israeli coasts by longshore currents, and most of the Nilotic sand is dispersed along the shallow continental shelf as an apron that pinches out northwards and westwards. This system of sediment supply has been active since at least the early Pleistocene (POMERANCBLUM, 1966; SAID, 1981). Haifa Bay acts as a sediment trap because it is bounded by two headlands, the Mount Carmel and Akko promontories. At present sea level the configuration of the bay prevents out-

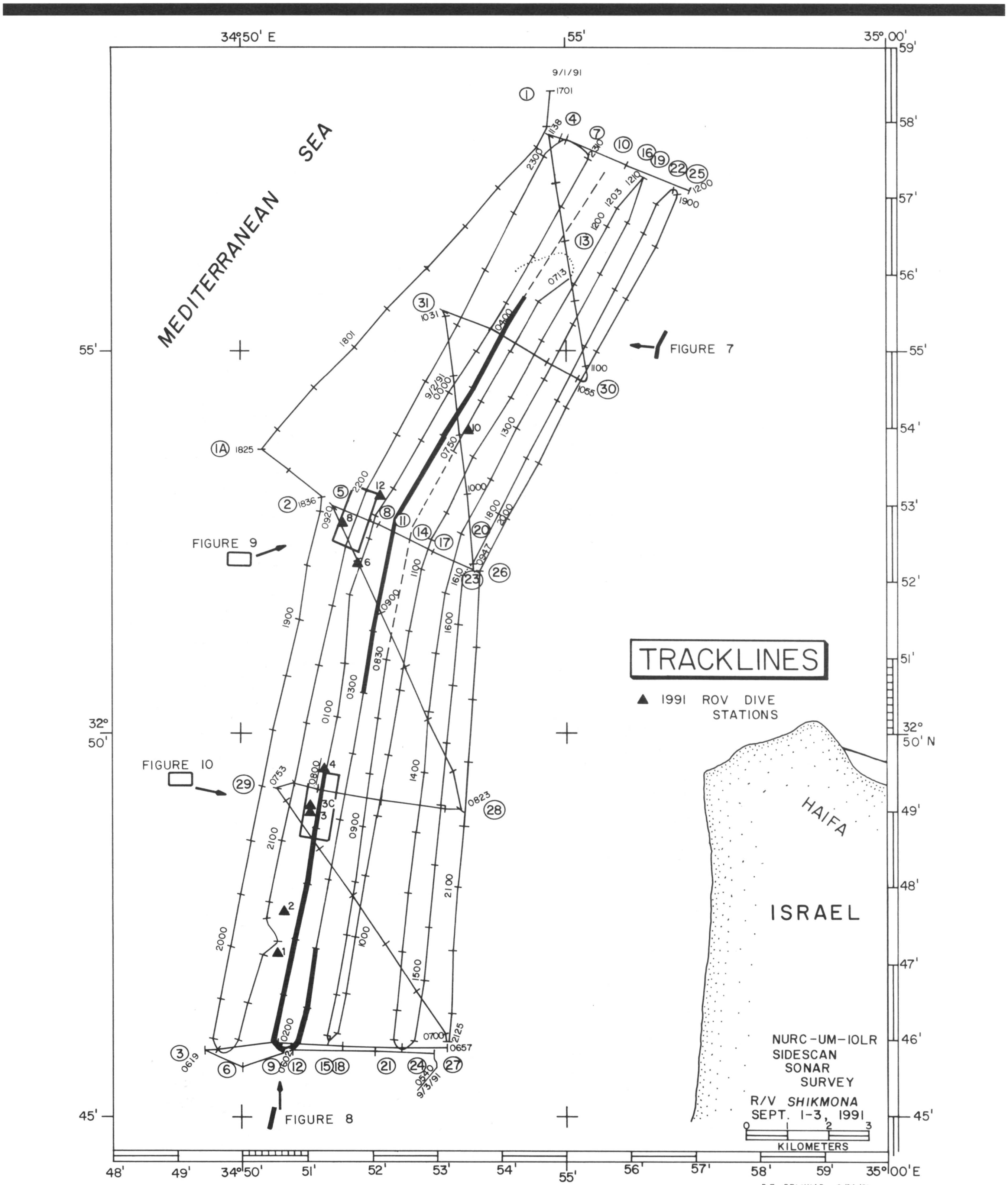

Figure 3. Location map of concurrent 3.5 kHz and side-scan sonar tracklines of *R/V Shikmona*, September, 1991 survey off Haifa. Figures used in text are located by: heavy lines for 3.5 kHz profiles, heavy open boxes for side-scan sonar areal coverage. October, 1991 ROV dive sites are indicated by solid triangles. Circled numbers 1–31 are turning points, used to identify lines (e.g., SM-91-8-9 indicates: Shikmona-1991-point 8 to 9).

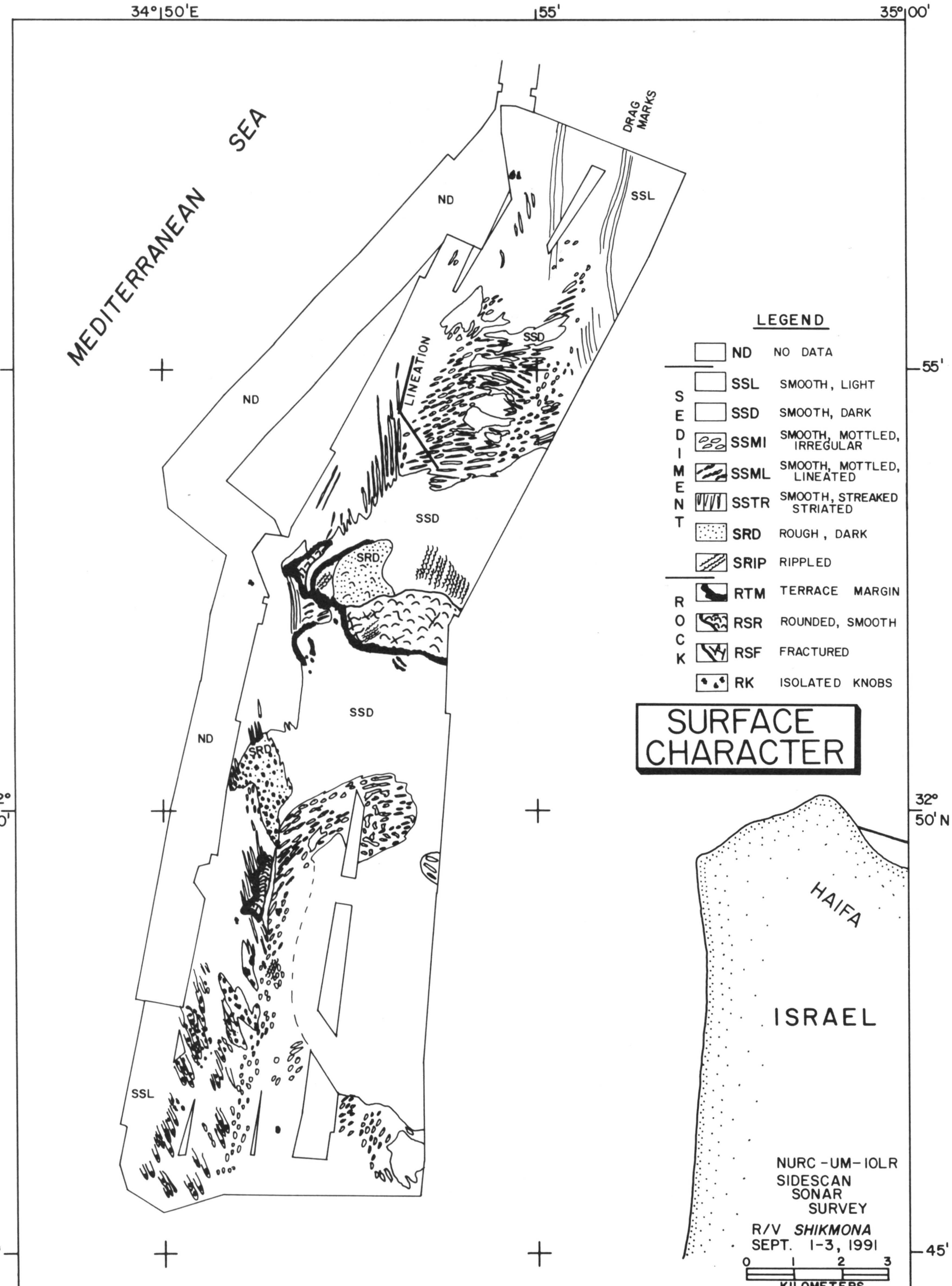

Figure 4. Side-scan sonar map of the Haifa, Israel outer shelf. EG&G SMS 260 digitally rectified images at 200-, 300- and 400-m scales, GPS navigation. Areas not covered by overlapping areal coverage indicated by blank polygons. Line SM-91-1-2 and SM-91-23 were primarily in water too deep for the length of cable available, thus returned no useable data (ND). Note the fractured terrains on the western side of the rocky terraces. Refer to Figure 3 for tracklines.

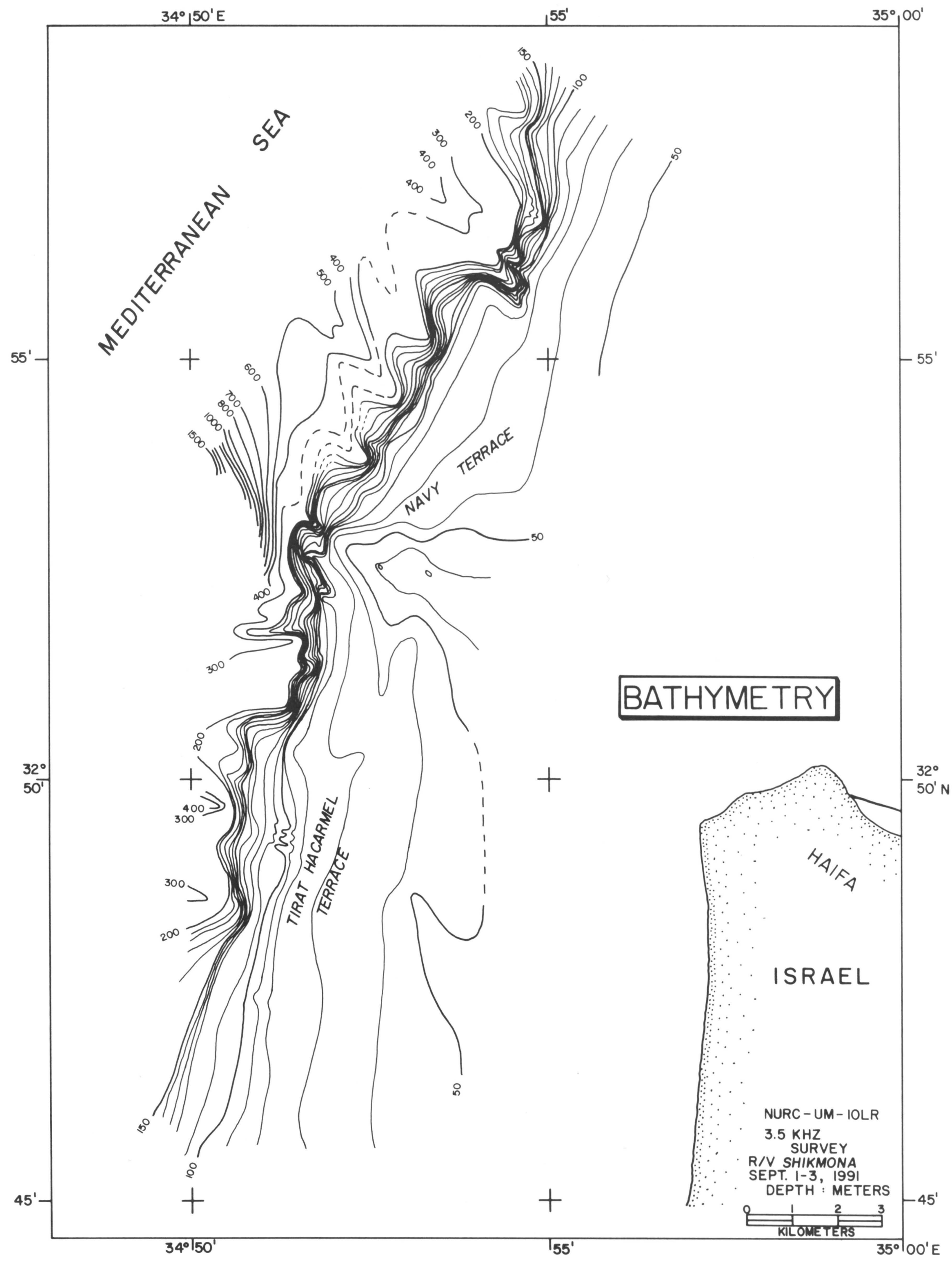

Figure 5. Bathymetric map of the Haifa, Israel outer shelf, based on new 3.5 kHz data along tracklines (Figure 3). GPS navigation. Contours outside tracklines from Almagor and Hall (1984). Depths in meters.

Figure 6. A modern coastal terrace cut by waves in Pleistocene eolianite, central Israel Mediterranean coast.

flow of longshore currents (Figures 1, 2). During higher sea levels the Akko headland was submerged, allowing sand bypassing toward the north, while during sea levels lower than 30 m from the present, the entire bay was emergent and had no indentation of the shoreline to interrupt the northward flow of the longshore current and its sandy load. Therefore, in both higher and lower sea levels, Nilotic sand was deposited farther to the north (ISSAR and KAFRI, 1972).

The accretion of sand bars along the nearshore zone leads to landward migration of the sand and to the accumulation of modern coastal sand dunes (GOLDSMITH *et al.*, 1982; CARMEL *et al.*, 1985). This sedimentological regime has controlled the sand transport and deposition in the present coastal environment since global sea level stabilized near its present position, approximately 6 ka (FAIRBANKS, 1989; BARD *et al.*, 1990a,b). In earlier periods the zone of coastal processes shifted its position in accordance with changing relative sea level, but the basic sedimentary regime along the Israeli coast and its dependance on the Nile River has been unchanged since the early Pleistocene. The Nilotic sand that accumulated on land in dunes in the Pleistocene, at various elevations and in harmony with shifting sea level, was lithified by continental carbonate cementation in many places to form eolianite (GAVISH and FRIEDMAN, 1969). This eolianite crops out along the present coast, and forms terraces with seaward-facing wave-cut escarpments (Figure 6).

RESULTS

Geomorphology and Sedimentology

The sedimentary regime, fluctuating sea levels, and the structural patterns along the distal continental shelf off Haifa combine to shape and expose rocky outcrops at depths of approximately 85–130 m at the Navy Terrace. Very steep escarpments delineate the Navy Terrace from the north and the west, and precipitous slopes to depths of more than 500 m are common (Figure 5). Slumps and landslides can be seen in many places and debris is common at the foot of the slopes (Figure 7). These steep slopes are the surface expression of the marine section of the Carmel Fault, down-throwing its northern flank, and the shelf-edge fault, down-throwing its western flank (NEEV *et al.*, 1976; MART, 1982, 1984). The faulted escarpments to the north and to the west probably acted as sources from which the sediment was removed and transported through the continental shelf and slope and into the marine basin. Most extensive outcrops of the sedimentary rocks of the Navy Terrace are in close proximity to the orthogonal escarpments of the intersecting faults, so that in

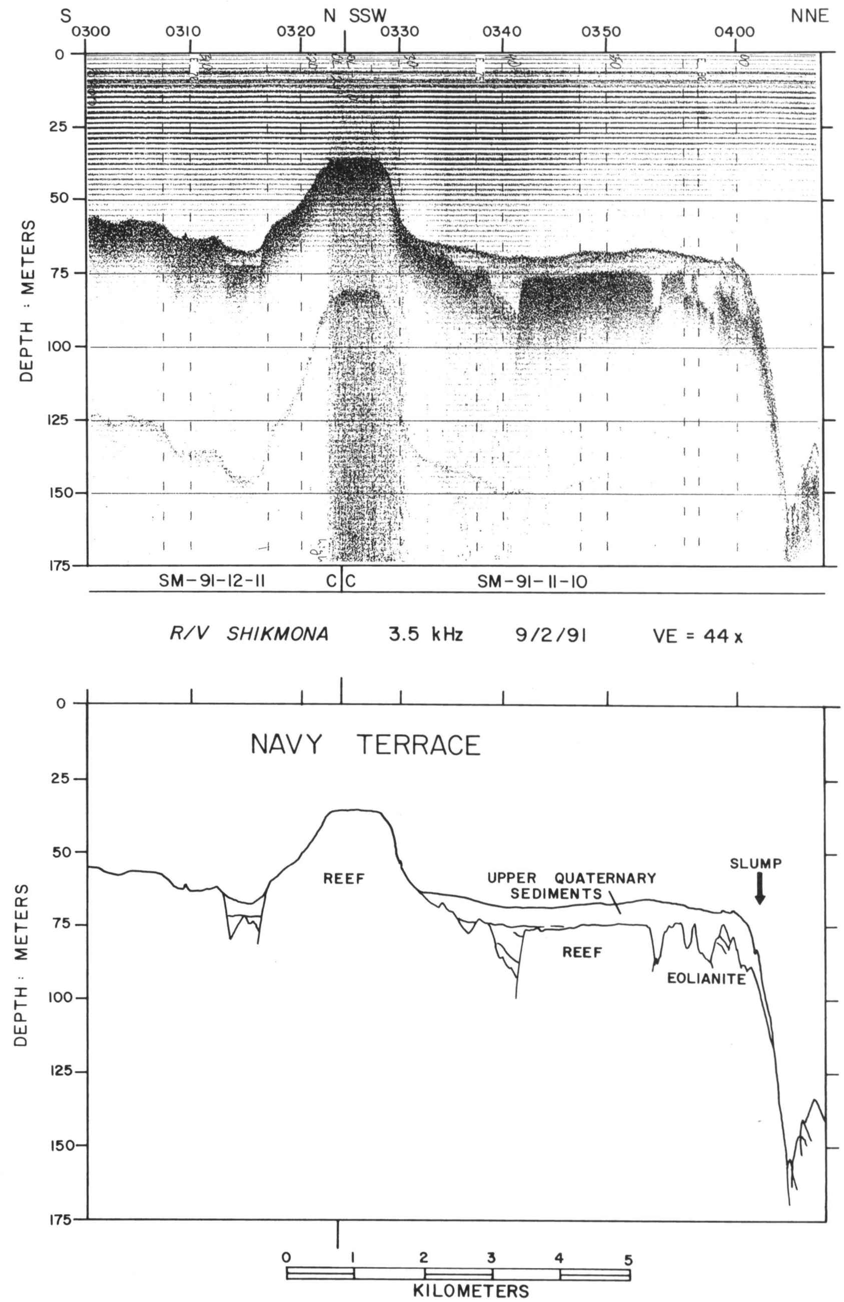

Figure 7. 3.5 kHz seismic reflection profile over the northern margin of the Navy Terrace. This faulted escarpment shows a steep drop of more than 75 m. Slumps and landslides are indicated by the detached block at the top of the escarpment (arrow) and the accumulated sediment at the foot of the slope. Location indicated in Figure 3.

some places the relief of the seafloor is extremely precipitous, commonly vertical (Figure 7). Separated pinnacles are encountered in some places. The rugged morphology is smoothed gradually with distance from the faulted steep slope landward, and the offsets in the eolianite decrease. Increasing distance from the major escarpments is also associated with increase in the thickness of the unconsolidated sediments that cover the eolianite subcrops (Figure 8). Flat-topped features buried under upper Quaternary sediments are inaccessible at present, but we speculate that they may be reefs (Figure 7).

The uneven distribution of the rocky outcrops is clearly discerned in the side-scan sonar images (Figure 9). They show abundant outcrops of layered sedimentary rocks near the faulted escarpments that delineate the Navy Terrace from the north and west, that are gradually buried under sedi-

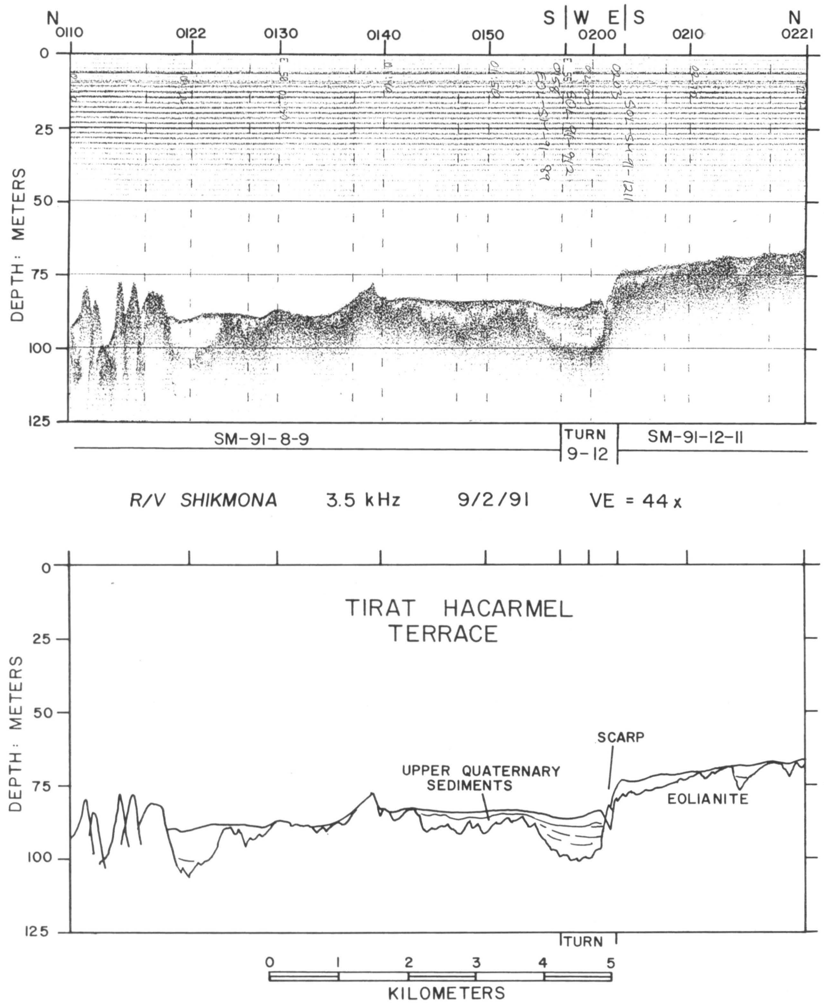

Figure 8. 3.5 kHz seismic reflection profile showing rugged morphology of eolianite subcrops in the Tirat HaCarmel Terrace, smoothed by sedimentary cover. Note the 15 m depth of sediment cover in some places. The step at 90 m depth corresponds to a turn in the line, but also reflects a terrace scarp. Location indicated in Figure 3.

ments toward the south and east (Figures 4, 9). The side-scan sonar survey also discovered a second cluster of similar outcrops, less extensive than the Navy Terrace but still clearly discernible. These crop out 5 km farther south, also at 85–130 m depth. These outcrops may be linked to the fault that transects the coastal plain and continental shelf of Tirat HaCarmel (Figure 2). There is reason to presume that removal of sediments and the exposure of the "Tirat HaCarmel Terrace" is the product of neotectonic activity at the intersection of Tirat HaCarmel Fault and the shelf edge fault as well.

Several series of ROV observations have been carried out on the Navy Terrace and "Tirat HaCarmel Terrace" since 1989. The recent observations indicate that the hills that comprise the Navy Terrace are morphologically asymmetric. Their seaward flanks are steep and form escarpments, while their eastern flanks dip gradually landwards, remarkably similar to the modern scarps on shore (Figure 6). The Tirat HaCarmel Terrace is composed of lower steps of a few meters relief, steep to undercut and overhanging on the west, sediment-covered on the east. The low outcrops are elongated north-south, or more symmetrical in plan view (Figures 4, 10). Sediment drifts occur to the NNW, with clearly defined scour pits on the SSE end (Figure 10). Sediment streaks composed of biogenic gravel and sand-sized material are elongated in the same orientation, in patches tens of meters wide and kilometers long. They are particularly evident on the southern flank of the Navy Terrace (Figures 4, 9). These features are presumed to be formed by NNW flowing bottom currents, directed at a small angle offshore of the general shelf-break trend. Both the Navy and Tirat HaCarmel Terraces are composed of eolianite.

ROV observations indicate that three principal types of sediments cover the eolianite of the terraces. The steeper parts of the terraces are covered by a biogenic layer, 1–2 m thick. Dense populations of benthic fauna, predominantly

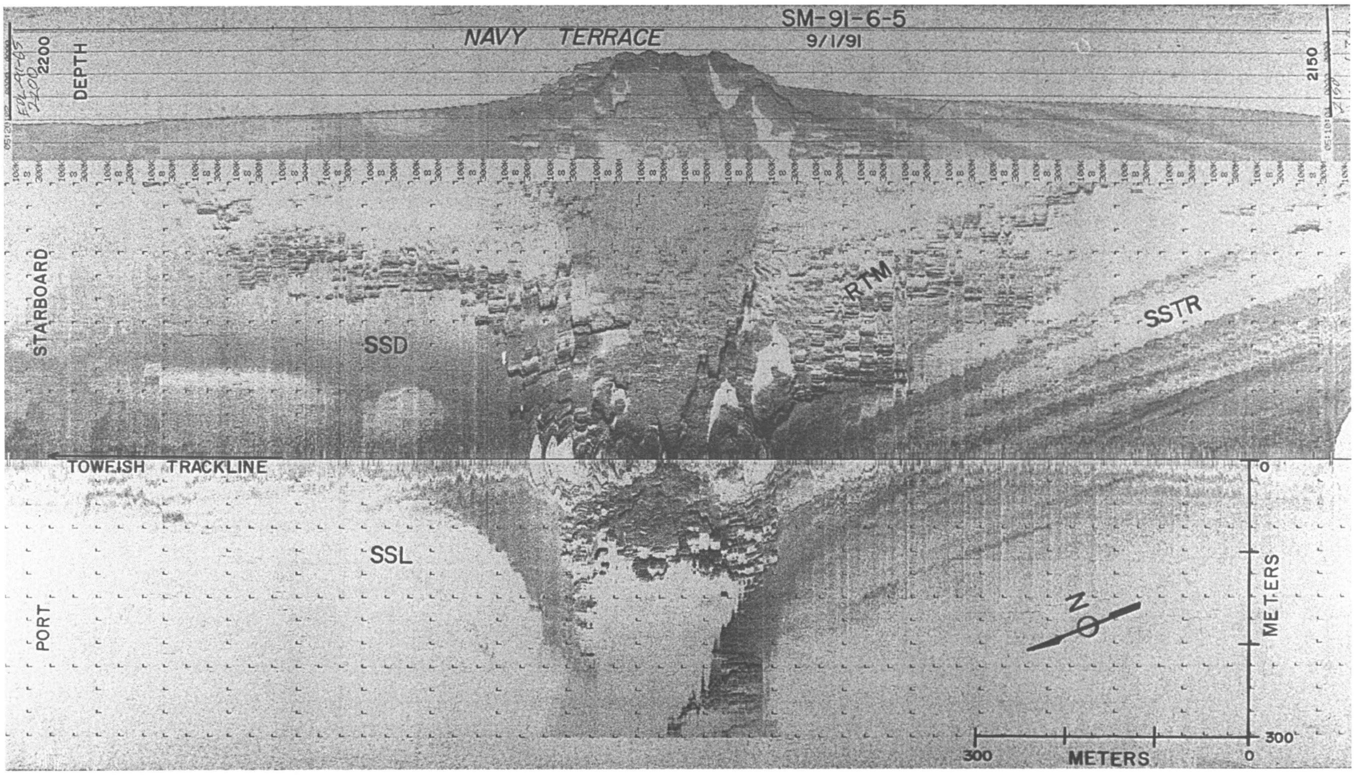

Figure 9. Side-scan sonar image of rocky outcrops of the Navy Terrace. Note the west-facing cliffs along many of the ridges. Location indicated in Figure 3. Abbreviations for surface character explained in Figure 4.

sponges, cling to the underlying hard substrate (Figure 11a). The escarpments on the flanks of the terraces cut across the lithified biogenic layer in some places, and uncover outcrops of the lower parts of the biogenic layer. This layer is conspicuously coarse and predominantly biogenic, and in some places a layer of coquina overlies the bedrock (MART and BELKNAP, 1991). The sedimentary rock contains long, sweeping crossbeds, a primary factor in the interpretation as eolianite. Eolianite outcrops were encountered in several places along the moderately sloping, landward-facing sections of the terraces (Figure 11b). Within a few tens of meters of the toe of terraces, and in the current-winnowed streaks, occur sandy gravels composed of carbonate fragments of molluscan shells, bryozoans, and corals (Figure 11c). Away from these coarser zones, the surface sediments are unconsolidated silts and clays, nearly devoid of sessile fauna. Bioturbation is active, however, by indwelling worms and decapods, and by surface activity of fish and invertebrates (Figure 11d).

Erosional channels and depressions were encountered on the gently sloping sections of the rocky terraces, cut unto the outcropping eolianite. These features could be the products of current erosion, or biogenic activity, or both. These features, the products of on-going erosion, are very different from the large escarpments that cut the terraces at their western flank. Thus, the escarpments seem to be relicts of the erosional regime that prevailed when the terraces were at the coastal zone.

Stratigraphy and Lithology

The eolianite in the coastal plain of Israel shows several depositional cycles, separated by layers of red loam, known locally as "hamra" (AVNIMELECH, 1952; YAALON, 1967; GAVISH and FRIEDMAN, 1969). Division of the entire Pleistocene sequence of alternating strata of eolianites and loams into formations was suggested by HOROWITZ (1979) and GVIRTZMAN *et al.* (1984), but the dating of all these units proved inconclusive, and the lateral correlations are thus ambiguous. Dating of the eolianite is difficult because index fossils are rare, and ^{14}C dating is restricted to the latest Pleistocene, and thus only to the upper parts of the sequence. RONEN (1975) used artifacts to date the red loam layers to the Acheulian, Mousterian and Epipaleolithic archaeological periods, > 250 ka, ca. 120–40 ka, and ca. 15–10 ka, respectively. In some places, where the stratification is very regular, the eolianites can be dated to the pre-Acheulian, pre-Mousterian, pre-Epipaleolithic, and post-Epipaleolithic periods. In most places, however, where the eolianite-loam stratification is not regular, dating remains dubious, and attempts to correlate discrete series of eolianite ridges to a certain period (*e.g.*, AVNIMELECH, 1952; ITZHAKI, 1961) cannot be supported by independent evidence. Likewise, attempts to correlate elevations of eolianite ridges, above or below the present sea level, with discrete Pleistocene climatic events (EYTAM, 1988) seem to disregard the sedimentological processes of accumulation and diagenesis of the eolianite, during intermittent marine regressions.

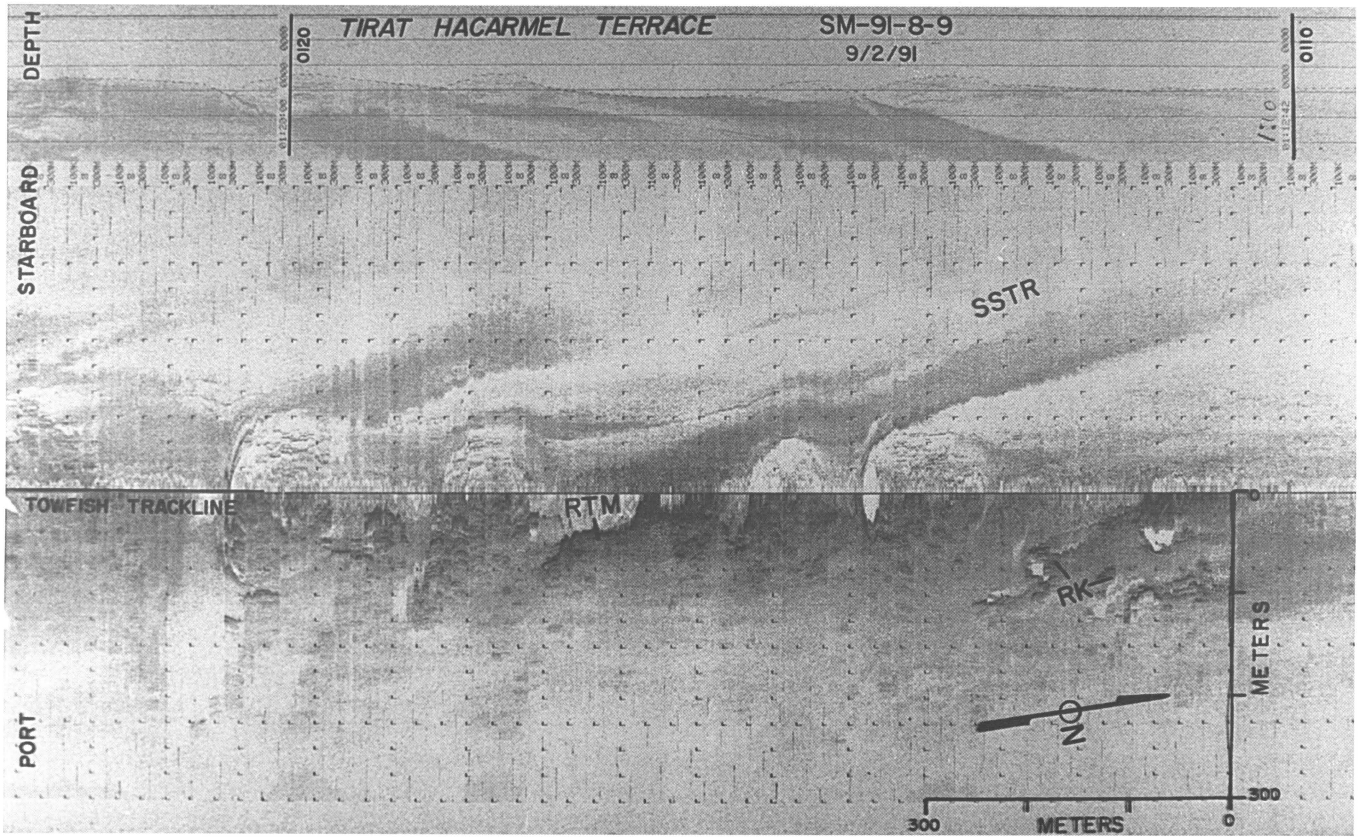

Figure 10. Side-scan sonar image of the Tirat HaCarmel Terrace, with outcrop of subdued relief, and scour marks that indicate NNW flowing bottom currents. Location indicated in Figure 3. Abbreviations for surface character explained in Figure 4.

A condition required for the lithification of the ridge sediments is the seasonal variation in rainfall, resulting in dissolution of biogenic allochems and reprecipitation of sparry cement.

YAALON (1967) and GAVISH and FRIEDMAN (1969) suggest that diagenesis of coastal sand dunes to form the eolianites is a continental process. Indeed, it is difficult to visualize how a sand dune could have maintained its morphology and internal crossbedded structure under the destructive effects of coastal waves during rising sea level. The abundance of shells of land snails in the eolianite and the absence of marine fossils strongly support the models of YAALON and GAVISH and FRIEDMAN. The accumulation, cementation, and preservation of coastal sand dunes in the Levant requires a period of relatively stable sea level, such as is found during the late Holocene. Paleogeographic reconstructions of the Middle- and Late Bronze Age periods indicate that coastal sand quantities were considerably less than at present (RABAN, 1983; SNEH and KLEIN, 1984). Because the lithification of the dunes occurred on land, either under stable sea-level conditions, or when sea level dropped, several series of eolianite hills could develop during a prolonged phase of marine regression that included several substages of stable sea level. The stable substage would be required to accumulate the sand into a large dune complex. The terrace at 120 m is the deepest identified, and is correlated with worldwide lowstand at this level. We have no specific dates on this terrace, but assume that the late Pleistocene is the most reasonable time of formation.

The comparable orientation of the multiple series of eolianite ridges in the coastal plain and continental shelf (Figure 1), and the present arcuate Israeli coastline is striking (*e.g.*, NEEV *et al.*, 1976, 1987). Some association between these ridges and the coastal environments seems plausible. However, the eolianite distribution is not restricted to the ridges, and it is encountered ubiquitously in the subsurface of the coastal plain of Israel (ISSAR, 1961; ISSAR and KAFRI, 1972). Thus, the correlation between the outcropping eolianite ridges and the subsurface eolianites seems complex. The paleogeographic significance of the various eolianite features can be deciphered, however. H. TZO'AR (*pers. comm.*, 1989) suggested that the series of elongated eolianite ridges are probably relict late Pleistocene coastal dunes, and the remainder represent irregular inland distribution of the dunes. Accumulation rates of sand dunes in the southern Levant in the Late Pleistocene and Holocene suggest centuries are required to accumulate these features (ZILBERMAN, 1992). The literature for this association in the Bahamas and Bermuda is extensive (*e.g.*, ESTEBAN and KLAPPA, 1983). Cementation, karst, and ca-

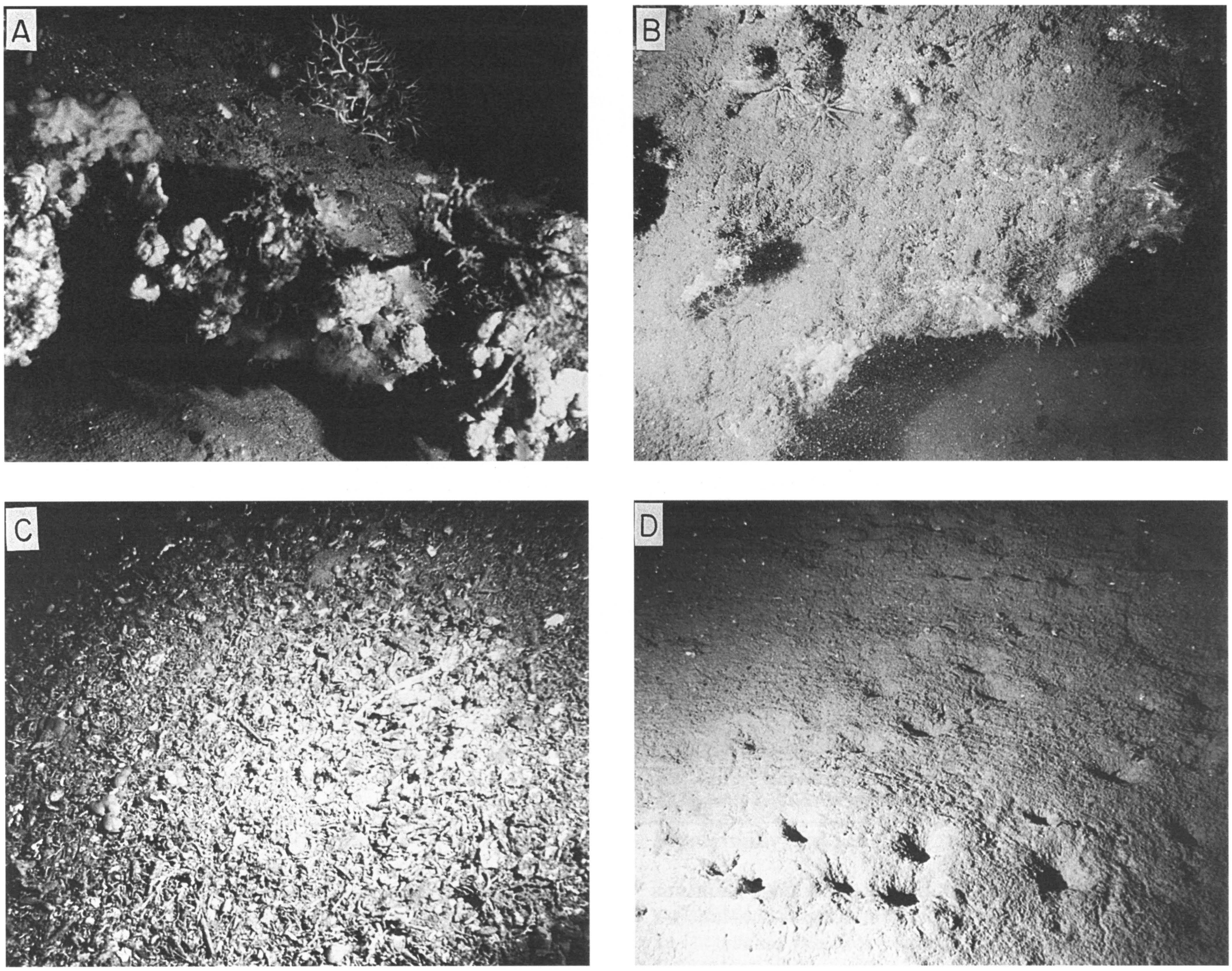

Figure 11. (a) Outcrop of the lithified biogenic cover of the Navy Terrace, overlain by a layer of sponges. Dive site 4, 10/4/91, 97 m depth. (b) Eolianite outcrop. Dive site 4, 10/4/91, 93 m depth. (c) Sandy gravel composed of carbonate fragments. Dive of 4/12/89, 83 m depth, outer edge of Navy Terrace, near 1991 site 8. (d) Mud with abundant bioturbation. Dive site 4, 10/4/91, 103 m depth. Locations indicated in Figure 3.

liche soils are typical features of such exposure, and some of these structures observed on the Israel shelf (Figure 11B) have strong similarities to caliche profiles (*e.g.*, ESTEBAN and KLAPPA, 1983, Figure 55).

The application of the local term "kurkar" to the Pleistocene carbonate-cemented sandstones in the coastal plain of Israel is misleading. Not only is the terminology not conventional, but it encompasses two types of rock, continental eolianite and marine calcarenite. Commonly, layers of calcarenite are deposited on the eolianites, as would be expected when the lithified dune became submerged. Alternatively, shell-bearing calcarenites could form the base of the section in a prograding sequence, as in the distal shelf settings of this study. The use of a single term for the two types of calcareous Pleistocene sandstones could lead to ambiguities of interpretation.

DISCUSSION AND CONCLUSIONS

The investigation of the Navy Terrace, Tirat HaCarmel Terrace and other parts of the distal continental shelf and upper slope off Haifa furnishes evidence pertaining to topics of regional geologic significance, such as eustatic sea-level changes and possible neotectonic modifications. The association of the eolianite terraces with sea-level variations during the late Pleistocene, and the extensive exposure of the eolianite terraces in proximity to faulted escarpments implies that neotectonic activity is associated with the erosion and down-slope transport of the sediments in the Navy and Tirat HaCarmel Terraces.

Large tracts of the continental margin of Israel are affected by faults that separate the gentle gradients of the continental shelf from the steep upper continental slope. Because these faults deform the uppermost sediments, their offset is considered neotectonic (MART, 1982, 1984). Such activity probably affected parts of the adjacent coastal plain as well. Indeed, earlier studies of historic earthquakes in the Levant (*e.g.*, BEN-MENAHEM *et al.*, 1976; POIRIER *et al.*, 1980; MART and PERECMAN, 1996) show that the coastal zone was affected by earthquakes repeatedly, and the recurrence time of destructive tremors is 250–350 years. These earthquakes seem independent of the tectonic activity of the Dead Sea Rift (BEN-MENAHEM *et al.*, 1976), and their tectonic association with the subsidence of the southeastern Mediterranean basin (MART, 1984) seems plausible. It should be emphasized that the Navy Terrace is a unique geomorphological feature along the marine escarpment of the Carmel Fault. Had the exposure of eolianite been a product of the displacements along the fault plane, other similar features could be expected along the fault. The absence of such phenomena supports the correlation of the Navy Terrace with the structural intersection between the Carmel and the shelf-edge faults, and the neotectonic significance of such intersections.

The finding that the late Pleistocene age eolianite ridges of the distal shelf are mostly covered by sediments suggests sediment supply to the distal shelf, reaching 15 m thickness in places, and that only enhanced erosion and sediment removal due to faulting leads to the outcropping of the eolianite of the fossil dunes. Mineralogical analyses of the upper sediments in the distal continental shelf showed abundant smectite (NIR, 1984), suggesting Nilotic origin. However, since such clay is also encountered along the coastal plain of Israel (STANLEY *et al.*, 1997), it seems that the Nilotic supply could also be indirect.

The submerged eolianite terraces along the distal continental shelf off Haifa are evidence that during the late Pleistocene local relative sea level was more than 100 m below the present level. Side-scan sonar, seismic-reflection profiling and ROV surveys show that features similar to the outcropping terraces are buried under sediment. The exposures of the Navy and Tirat HaCarmel Terraces are probably the product of neotectonic activity along the coast of the Levant, but the seismic evidence of continuity between the exposed and covered ridges indicates that the neotectonic offset of these ridges was minimal. Displacements took place mainly in proximity to the fault planes, and did not affect the general level of the outer shelf. These terraces may correlate with similar features worldwide produced at the late Pleistocene lowstand. For example, lowstand shorelines on the east coast of the U.S. have been identified at depths of 90 to 140 m, but there is little specific information on their age (EMERY and UCHUPI, 1972). FAIRBANKS (1989), on the other hand, has the best record available for sea-level lowstands at ca. 17 ka in coral reefs from Barbados. The comparability of depths between the Israeli shelf and Barbados lowstand depths suggests only slight differences in local tectonic warping, in geoidal shifts, or in regional oceanographic controls on sea level over this time period. This coherence suggests that the submerged terrace off northern Israel represents a real eustatic signal.

ACKNOWLEDGMENTS

We thank ROV pilots Sue LaRosa and Helga Sprunk, who were essential to the completion of this study. We are grateful to Ivar Babb, William Duffy, Ivor Liberman, Lance Stewart, and the crew of the *R/V Shikmona* for their help and cooperation. We thank Hanna Barnard for several figures. This study was supported by the U.S. National Oceanic and Atmospheric Administration through the National Undersea Research Center at the University of Connecticut at Avery Point (NURC-UCAP), and by the Administration of Earth Resources of Israel's Ministry of Energy and Infrastructure. Annotated videos, dive logs, and still photographs are archived at NURC-UCAP, the Department of Geological Sciences, University of Maine, and at IOLR, Haifa, Israel.

LITERATURE CITED

ALMAGOR, G. and HALL, J.K., 1984. Morphology of the Mediterranean continental margin of Israel. *Geological Survey of Israel Bulletin.*, 77, 1–31.

AVNIMELECH, M., 1952. Late Quaternary sediments of the coastal plain of Israel. *Bulletin of the Research Council of Israel*, 2, 51–57.

BARD, E.; HAMMELIN, B., and FAIRBANKS, R. G., 1990a. U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130,000 years. *Nature*, 346, 456–458.

BARD, E.; HAMELIN, B.; FAIRBANKS, R. G., and ZINDLER, A., 1990b. Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. *Nature*, 345, 405–410.

BEN-AVRAHAM, Z., 1978. The structure and tectonic setting of the Levant continental margin, eastern Mediterranean. *Tectonophysics*, 146, 313–331.

BEN-MENAHEM A.; NUR, A., and VERED, M., 1976. Tectonics, seismicity and structure of the Afro-Eurasian junction—the breaking of an incoherent plate. *Physics of Earth and Planetary Interiors*, 12, 1–50.

CARMEL, A.; INMAN, D.L., and GOLIK, A., 1985. Directional wave measurement at Haifa, Israel and sediment transport along the Nile littoral cell. *Coastal Engineering*, 9, 21–36.

EMERY, K.O. and NEEV, D., 1960. Mediterranean beaches of Israel. *Geological Survey of Israel Bulletin.*, 26, 1–26.

EMERY, K.O. and UCHUPI, E., 1972. Western North Atlantic Ocean: Topography, Rocks, Structure, Water, Life, and Sediments. *American Association of Petroleum Geologists Memoir 17.* Tulsa OK, 532p.

ESTEBAN, M. and KLAPPA, C.F., 1983. Subaerial exposure environment. *In:* P.A. SCHOLLE; D.G. BEBOUT, and C.H. MOORE (eds.), *Carbonate Depositional Environments, American Association of Petroleum Geologists Memoir* 33, pp. 2–95.

EYTAM, Y., 1988. The Shallow Structure and the Geologic Processes of the Inner Shelf off Northern Israel in the Late Pleistocene. Unpub. Ph.D. Dissertation, Israel, Tel Aviv University, 100p.

FAIRBANKS, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature*, 342, 637–642.

GARFUNKEL Z.; ARAD, A., and ALMAGOR, G., 1979. The Palmahim disturbance and its regional setting. *Geological Survey of Israel Bulletin.*, 72, 1–56.

GAVISH, E. and FRIEDMAN, G.M. 1969. Progressive diagenesis in Quaternary to late Tertiary carbonate sediments. *Journal of Sedimentary Petrology*, 39, 980–1006.

GOLDSMITH, V. and GOLIK, A., 1980. Sediment transport model of the southeastern Mediterranean coast. *Marine Geology*, 37, 147–175.

GOLDSMITH, V.; BOWMAN, D.; KILEY, K.; BURDOCK, B.; MART, Y, and SOFER, S., 1982. Morphology and dynamics of crescentric bar systems. *Proceedings XVIII Coastal Engineering Conference II*, pp. 941–953.

GVIRTZMAN, G.; SHACHNAI, E.; BAKLER, N., and ILANI, S., 1984. Stratigraphy of the Kurkar Group (Quaternary) of the coastal plain of Israel. *Geological Survey of Israel Current Research 1983/84*, pp. 70–82.

HALL, J.K., 1980. *Bathymetric chart of the southeastern Mediterranean*. Geological Survey of Israel Report MG/13/80. 1:625,000.

HALL, J.K. and BAKLER, N., 1975. *Detailed bathymetric and shallow seismic surveys at five locations along the Mediterranean coast of Israel*. Geological Survey of Israel UN/UNDP Offshore Dredging Project, Field Report 1/75.

HOROWITZ, A., 1979. *The Quaternary of Israel*. London: Academic, 394p.

ITZHAKI, Y., 1961. Contribution to the study of the Pleistocene in the coastal plain of Israel. *Geological Survey of Israel Bulletin*, 32, 1–9.

ISSAR, A., 1961. The Plio-Pleistocene geology of the Ashdod region. *Bulletin of the Research Council of Israel*, 10G, 173–182.

ISSAR, A. and KAFRI, U., 1972. Neogene and Pleistocene geology of the western Galilee coastal plain. *Geological Survey of Israel Bulletin*. 53, 18p.

KAFRI, U., 1970. Pleistocene tectonic movements in the coastal plain of Israel emphasizing the Mount Carmel area. *Israel Journal of Earth Sciences*, 19, 147–152.

MART, Y., 1982. Quaternary tectonic patterns along the continental margin of the southeastern Mediterranean. *Marine Geology*, 49, 327–344.

MART, Y., 1984. The tectonic regime of the southeastern Mediterranean continental margin. *Marine Geology*, 55, 365–386.

MART, Y. and BELKNAP, D.F., 1991. Origin of Late Pleistocene submerged marine terraces on the outer continental shelf, northern Israel. *Geo-Marine Letters*, 11, 66–70.

MART, Y.; GALIL, B., and BELKNAP, D.F., 1990. Submerged marine terrace on the deep continental shelf off Israel. *In:* Y. MART and B. GALIL (eds.), *The Mediterranean Continental Margin of Israel*. Tel Aviv: Tel Aviv University, (abstract).

MART, Y. and PERECMAN, I., 1996. Neotectonic activity along the coast in Caesarea, central Israel. *Tectonophysics*, 254, 139–153.

MICHELSON, H., 1970. The Geology of the Carmel Coast. Unpub. Thesis, Hebrew University, Jerusalem, Israel, 65p. (in Hebrew).

NEEV, D.; ALMAGOR, G.; ARAD, A.; GINZBURG, A., and HALL, J.K., 1976. The geology of the southeastern Mediterranean. *Geological Survey of Israel Bulletin*. 68, 1–51.

NEEV, D.; BAKLER, N., and EMERY, K.O., 1987. *Mediterranean Coasts of Israel and Sinai*. New York: Taylor and Francis, 130p.

NIR, Y., 1984. Recent Sediments of the Israel Mediterranean Continental Shelf and Slope. Unpub. Ph.D. Dissertation, Sweden, University of Gothenburg, 149p.

POIRIER, J.P.; ROMANOWICZ, B., and TAHER, M.A., 1980. Historical seismicity in the Near and Middle East, North Africa, and Spain from Arabic documents (VII'th–XIII'th century). *Bulletin of the Seismological Society of America*, 70, 2185–2201.

POMERANCBLUM, M., 1966. The distribution of heavy minerals and their hydraulic equivalents in sediments of the Mediterranean continental shelf of Israel. *Journal of Sedimentary Petrology*, 36, 162–174.

RABAN, A., 1983. Recent maritime archaeological research in Israel. *International Journal of Nautical and Underwater Exploration*, 12, 229–251.

ROHRLICH, V. and GOLDSMITH, V., 1984. Sediment transport along the Southeast Mediterranean: a geological perspective. *Geo-Marine Letters*, 4, 99–103.

RONEN, A., 1975. The Paleolithic archaeology and chronology of Israel. *In:* F. WENDORF and A.E. MARKS (eds.), *Problems in Prehistory. North Africa and the Levant*. Dallas, Texas: Southern Methodist University Press, pp. 229–248.

SAID, R., 1981. *The Geological Evolution of the Nile River*. New York: Springer-Verlag, 151p.

SLATKINE, A. and ROHRLICH, V., 1963. Sediments du Quaternaire de la plaine de Haifa. *Israel Journal of Earth Sciences*, 12, 159–206.

SNEH, Y. and KLEIN, M., 1984. Holocene sea level changes at the coast of Dor, southeastern Mediterranean. *Science*, 226, 831–832.

STANLEY, D.J.; MART, Y., and NIR, Y., 1997. Clay mineral distribution to interpret Nile cell provenance and dispersal: II. Coastal plain from Nile delta to northern Israel. *Journal of Coastal Research*, 13, 506–533.

YAALON, D.H., 1967. Factors affecting the lithification of eolianite and interpreting of its environmental significance in the coastal plain of Israel. *Journal of Sedimentary Petrology*, 37, 1189–1199.

ZILBERMAN, E., 1992. The Late Pleistocene sequence of the northwestern Negev flood plains—A key to reconstructing the paleoclimate of southern Israel in the last glacial. *Israel Journal of Earth Sciences*, 41, 155–167.